AD NUMBER
AD844691
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usaf, ltr, 25 jan 1972

ADVANCED ARRAY RESEARCH

Quarterly Report No. 3
1 September 1968 through 30 November 1968

George Hair, Program Manager
Area Code 214, 238-3473

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Contract No. F33657-68-C-0867
Beginning 15 February 1968
Ending 14 February 1969

Prepared for
AIR FORCE TECHNICAL APPLICATIONS CENTER
Washington, D.C. 20333
attn: VSC

Sponsored by
ADVANCED RESEARCH PROJECTS AGENCY
Nuclear Test Detection Office
ARPA Order No. 624
AFTAC Project No. VT/7701

5 December 1968

TEXAS INSTRUMENTS
INCORPORATED
SCIENCE SERVICES DIVISION

5 December 1968

Air Force Technical Applications Center
VELA Seismological Center
Headquarters, USAF
300 N. Washington Street
Alexandria, Virginia 22314

Attention: Major Carroll F. Lam

Subject: Quarterly Report No. 3 for period 1 September 1968 through 30 November 1968

Identification:
AFTAC Project No.: VT/7701
Project Title: Advanced Array Research
ARPA Order No.: 624
ARPA Program Code No.: 7F10
Name of Contractor: Texas Instruments Incorporated
Contract Number: F33657-68-C-0867
Effective Date of Contract: 15 February 1968
Amount of Contract: $341,000
Contract Expiration Date: 14 February 1969
Project Manager: George Hair
Area Code 214, 238-3473

TECHNICAL STATUS

Technical progress during the third project quarter is reviewed by task. Major accomplishments, problems encountered and plans for the fourth quarter are presented.

During the third quarter the emphasis was changed on two tasks. More emphasis was placed on the Task C objective of developing array processing techniques specifically designed to take advantage of the unique capabilities of 3-component long-period arrays. The study will be mostly theoret-

ical and will concentrate on techniques for extracting Rayleigh wave signals from ambient noise and for separating overlapping Rayleigh wave signals. Task F was modified to increase the analytical comparisons of different techniques for computing high-resolution frequency-wavenumber spectra. The development of and research with an 870A computer program for computing and displaying wavenumber spectra has been indefinitely postponed.

Task A - Research on Adaptive Processing Techniques

> Continue studies of time-adaptive filtering techniques. Emphasis should be on determining methods of specifying optimum parameters for convergence and generalized signal models. Investigate the feasibility of off-line programming of current digital multichannel processors using time-adaptive techniques rather than conventional filter design techniques.

An investigation of the feasibility of processing Fourier transformed data using the Widrow adaptive algorithm was completed. Expected advantages of this frequency-domain processing include (1) a simplification of the constraint equations describing the signal models, (2) higher processing speed by using fast Fourier transform techniques, (3) greater understanding of the Widrow algorithm and (4) convergence rates, or time constants, which are individually selected and adjustable at each frequency. This latter item is a fundamental advantage excluded from time domain processing, in which case a single convergence rate applies. A description of this frequency-domain approach to adaptive data processing will be included in the next special report.

Problems which occur in time-domain processing of real time data have been identified, and methods of solution in the form of modifications to the basic algorithm have been established. The failure of a single sensor is a problem which can adversely affect adaptive processing. Very

strong signals or noise can cause the filter system to become unstable. When a sensor is to be added to or delet d from the array, the adjusting of the filtering system to satisfy the signal models without generating a transient is another problem. The program has been written and experimental data gathered to illustrate the behavior of the on-line algorithm during realistic situations.

Development has continued on the program to implement multiple constraints (multiple signal models). Data has been processed passing the upward travelling wave while rejecting the downward travelling wave, and in another case signal processing included passage of both upward and downward travelling waves. The latter case showed some signal-to-noise improvement over the former. A special report is in preparation describing the multiple constraint program and results.

Plans for the next quarter include application of the programs necessary to simulate real-time data processing. Relative merits of the applied solutions of the problems occurring in this processing are to be found. Additional data will be processed using multiple signal models.

Task B - Evaluation of the Expanded SP Array at TFO

Task C - Long-Period Three-Component Array Processing

> Using data from the expanded short-period array at the Tonto Forest Seismological Observatory (TFSO), determine the effectiveness of such an expanded array compared to that of smaller arrays for improving signal-to-noise ratios at such body-wave limited sites. In addition, data from the long-period arrays at TFSO and Uinta Basin Seismological Observatory to be supplied by the project monitor should be analyzed for the purpose of specifying optimum processing techniques.

Analysis of TFO 37-element Array

A four-hour sample obtained during the recording trip in June has been selected for analysis. Playbacks indicate that 33 of the 37 elements are usable. A two-hour portion of this sample, free of recognizable events, is being transferred to the S/360 where the analysis will be performed. Preprocessing will include despiking, anti-alias filtering, and resampling to an 0.288 second sample period. The anti-alias filters have been designed to have a response within the pass band which will tend to whiten the data. This will effectively eliminate leakage problems due to spectral window effects in the frequency domain analysis.

Crosspower matrices at appropriate frequencies will be calculated from the data. These matrices will be used in the frequency domain design and evaluation of multichannel-filter (MCF) processors. They will also be used for wavenumber analysis of the noise sample.

Theoretical Study of 3-Component Long-Period Processing

A theoretical study of the utility of horizontal-component long-period seismometers for signal extraction has been initiated. At the present time this study is directed to the problem of extracting Rayleigh-wave signals from ambient noise. This work follows the procedures used in a previous study of vertical-component long-period arrays.[1] The necessary programs have now been completed. As a test case, a 7-element hexagonal-grid array of 3-component instruments was considered. Spacing between nearest elements is 30 km. The noise field is composed of isotropic Rayleigh-wave energy propagating at 3 km/sec with 1% random noise added. The signal is a Rayleigh-wave propagating westward at 3 km/sec. MCF SNR improvement in this situation for a 7-element vertical-seismometer array is shown in figure 3 of the report cited above. When the horizontal seismometers are added,

1. Advanced Array Research, Special Report No. 9, 23 January, 1968.

MCF SNR improvement in the range 0.0 to 0.10 Hz increases by 1-5 db. It is particularly noteworthy that dips in the vertical-component array performance curves, caused by space aliasing, are eliminated by the addition of the horizontal seismometers.

Immediate plans are to evaluate the effects of higher random noise levels and of Love-wave noise on the horizontals. In addition, the performance in partially directional noise fields will be examined. It is planned to complete study of the 7-element array before proceeding to 19- and 37-element arrays.

Separation of Time-Overlapping Rayleigh-Wave Events

The work described here was begun under a no-cost time extension of the LASA Evaluation program and is now continuing as part of the Advanced Array Research program.

Five long-period tapes, each including two distinct events were received from the LASA Data Service. Single location 3-component playbacks were made from the tapes. These were used along with associated PDE reports and LASA bulletins to determine the usefulness of the tapes for studying the interfering event problem. In one case the two events both occurred in the Kurile Islands with a two-minute difference in origin times. In the other four cases the arrival times of the two events at LASA were sufficiently different that significant overlapping did not occur. As a result, no further effort to process this data has been made.

Some previous work on the interfering event problem was reported in LASA Special Scientific Report No. 23.[2] Two 5-channel MCF's were designed using the A0 and C ring vertical sensors for separating overlapping events. In the first case the separation between the propagation vectors for the two events was 55° while in the second case it was 28°.

2. Large Array Signal and Noise Analysis, Special Scientific Report No. 23, 20 September, 1968.

Suppression of the interfering event in these two cases was about 18 db and 12 db respectively. Thus the C ring appears to have limited resolution ability as a result of its small aperture. The experiments were repeated using the A0 and E ring sensors in hopes that the larger aperture would provide better performance. Unfortunately the E ring MCF was inferior to the C ring in the 55° case and about equivalent to the C ring in the 28° case. It was tentatively concluded that signal inequalization across the larger aperture array precluded effective utilization of its increased resolution.

In an effort to confirm this we have designed two sets of prediction filters to predict the A0 vertical trace for an event coming from Hokkaido. The first set uses the C ring verticals while the second set uses the E ring verticals. The prediction error for the C ring filters at the peak power frequency (0.04 Hz) was about -42 db, but for the E ring filters was only about -5 db. Thus signal inequalization for the larger aperture array does indeed result in strong reduction of the multiple coherence, and it appears that the signal separation results cited above were valid.

We are currently studying the use of horizontal seismometers in the signal separation problem. One MCF using both vertical and horizontal sensors was evaluated during the LASA program, but did not seem to improve the performance of the corresponding vertical seismometer MCF.[2] Despite this fact, the strong similarity between the vertical and horizontal inline traces for recorded events suggests that the horizontals should be useful.

The approach under consideration is to do single location three-component processing at the various seismometer locations of the array. Subsequent velocity processing can then be performed on the resultant outputs. A theoretical comparison of two different methods of three-component

2. Large Array Signal and Noise Analysis, Special Scientific Report No. 23, 20 September, 1968.

processing has been made. In the first case the horizontal components are trigonometrically rotated to form a component transverse to the propagation vector of the desired signal. This component then contains Love-wave energy from the desired epicenter and both Love-wave and Rayleigh-wave energy from the interfering epicenter. A single channel prediction filter is designed to predict the vertical component of the interfering Rayleigh-wave from this horizontal component. The resultant prediction error trace then includes the desired Rayleigh-wave plus error in doing the prediction. This error results from the Love-wave energy on the rotated horizontal component.

In the second case a three-channel MCF is designed using the vertical and unrotated horizontal components to enhance the desired Rayleigh-wave on the vertical. The theoretical comparison of the two techniques was made in the frequency domain, and in theory is independent of frequency. The results indicate a substantial superiority for the second approach. As an example, the following results were obtained when the angle between the two-propagation vectors is 60°, the ratio of Love-wave to Rayleigh-wave power for both events is 0.5, and the ratio of desired event Rayleigh-wave power to interfering event Rayleigh-wave power is 0.01. For the first approach, the normalized error in predicting the interfering Rayleigh-wave off the vertical was found to be about 0.16, indicating about 8 db suppression of the undesired energy. Corresponding results for the signal extraction approach indicate about 17.5 db suppression. Evaluation of this second approach with real data for a single three-component location is now in progress.

If this experiment provides results in reasonable agreement with the theory, the next step is to evaluate the additional gains to be realized by velocity processing the outputs of an array of such three-component processors. It is not clear how to theoretically study this question. It is planned,

therefore, to actually perform three-component single-site processing at the various array locations, followed by either beamsteer or MCF processing of the outputs. Both techniques will be evaluated.

Task D - NORSAR Signal and Noise Analysis

> Using supplied data, investigate the noise characteristics and surface-wave detection capability of a partially installed Large Aperture Seismic Array at a location to be provided by the project officer.

Software packages have been developed which will read and process long-period data from NORSAR. Capabilities to date include:

- Read, demultiplex, and plot the data from merged tapes received from LASA Data Services.
- Quality check data by computing mean, rms values and number of spikes on each trace of each record.
- Rotation of horizontal components.
- Multichannel Cooley-Tukey transformation of multiplexed data.
- Single-channel power-density spectra and two channel coherence estimates.

Processing of data has been limited due to unavailability of usable data. Three long-period merged tapes have been received from LDS to date. These tapes consist of 9 channels of data containing information recorded from three component elements located at each of the three sites, Oyer, Trysil, and Faldalen, plus 3 channels of weather information from the latter site.

Two of the tapes appear to be blank except for an end-of-file which was encountered when attempting to read the tape. The third tape has

been processed to a limited degree. The Fåldalen site appeared inoperative during most of the period covered by the tape. Various channels of the other two sites frequently contained a segment of bad data.

Noise Analysis

Single-channel power density spectra have been computed from two noise samples for the three components located at Trysil. Analysis of the spectra show a single energy peak at a period of approximately 16 seconds. Energy at periods longer than 25 seconds appears to be significantly higher on the horizontal components than the vertical. Absolute level of the spectra could not be established due to inadequate calibration data.

Power spectra computed from the Oyer data could not be properly analyzed. The system noise level or some other phenomenon has affected the data.

Signal Analysis

A program to rotate the horizontal components to inline and transverse to the direction of propagation and to plot both original and rotated data was applied to an event occurring on May 2, 1968 in Iran. Distance to the event was approximately 40 degrees, the magnitude was 5.6, and the depth unknown. Three distinct phases were identifiable from the plots corresponding to Shear, Love and Rayleigh on the basis of travel time and expected velocities. The velocities, as measured from observed move-out across the array for each of these phases, were 6.5 km/sec, 4.2 km/sec, and 3.7 km/sec, respectively. The shear phase was predominately 20-25 second period energy. Love wave energy varied from 40 sec to 25 sec periods, and Rayleigh varied from 30 sec to 20 sec periods.

Rotation of the horizontal axis to enhance Love and eliminate Rayleigh on the transverse instrument, and vice versa for the inline instrument, was successful to the degree that both phases were made easily recognizable.

Plans

Additional data has been requested from LDS. The two long-period tapes which appeared blank will be investigated and possibly regenerated by LDS. A NORSAR short-period tape has been received by LDS and will be copied and sent to us within the next week. Capabilities to process the short-period tape will be developed similar to that for the long-period data.

Other signals from known test sites will be studied as data are available. Coherence and similarity of signal waveforms between the three sites will be studied. Spectral analysis of long- and short-period data will be continued.

Task E - Analysis of WMO Vertical and Horizontal Component Ambient Noise

Continue studies of noise recorded with the experimental array at Wichita Mountains Seismological Observatory.

A new prediction technique for analyzing data whose spectrum contains lines has been investigated. The advantages of this technique are its' simplicity and the fact that no signal model is required.

Synthetic data corresponding to spectral lines with different frequencies and phases were added to the noise sample. The conventional and Burg's prediction operators, and the maximum entropy spectrum were then computed. Special attention was given to comparison of the two operators in terms of prediction decay rate and prediction error.

Programs were written and checked out to design narrow band-pass feedback filters. These filters were applied to both the original and predicted noise sample as an aid in evaluating the performance of the prediction operators on each line.

Plans for future development and analysis are:

- To improve the conventional prediction operators by modification of their z-transform so as to bring their poles nearer the unit circle and thus narrow their pass bands.

- To investigate adaptive prediction of spectral line noise components.

- To apply these techniques to the ambient noise samples collected at WMO with the special vertical/horizontal array. The modes, velocities and directions of propagation of the seismic energy appearing as lines in the WMO spectra will be determined. An attempt to infer the sources of such noise components will be made.

Task F - Research on High-Resolution Frequency-Wavenumber Spectral Estimation

Investigate the ability to detect and locate seismic events through the continuous computation and display of high-resolution frequency-wavenumber spectra.

Basic theoretical investigations of high-resolution frequency-wavenumber spectra were continued during the third project quarter. Plans to simulate on-line application of high-resolution spectra were postponed in order to permit increased emphasis on the Task C investigation of three-component array processing techniques.

The theoretical investigations are directed toward selecting the particular high-resolution technique which is most suitable for use as a detection and localization tool.

For a crosspower spectrum matrix of the form $\Phi = pI + \sum_{j=1}^{n} V_j V_j^H$, the high resolution spectrum

$$Q = \frac{1}{U^H \Phi^{-1} U}$$

was found to be equal to the ratio of two determinants. These determinants are the same as shown in the last quarterly report except that additional terms $V_j^H V_k$ are added in the appropriate place below and to the right of the determinant elements shown there. Using this determinant ratio, the crosspower spectrum matrix $\Phi = pI + VV^H + WW^H + XX^H$ was studied. Whenever the probe vector U was not a linear combination of V, W, and X, the "inverse" spectrum Q approached zero as the random noise approached zero. Whenever the probe vector U was equal to either V, W, or X, the spectrum correctly reflected the amplitude squared of the corresponding vector as the random noise term approached zero. For probe vectors which were linear combinations of V, W, and X, the corresponding "inverse" spectrum approached a weighted sum of $|V|^2$, $|W|^2$, $|X|^2$, $|V^H W|$, $|V^H X|$, and $|W^H X|$ as the random noise approached zero. By diagonalizing the crosspower spectrum matrix, several interesting properties about the spectra $P = U^H \Phi U$, $Q = \left[U^H \Phi^{-1} U\right]^{-1}$ and $R = \left[U^H \Phi^{-1} U\right] / \left[U^H \Phi^{-2} U\right]$ were determined. First, all three spectra agree when U points in the same direction as one of the eigenvectors of the crosspower spectrum matrix. Second, for all other unit vectors U, it is true that $P>Q>R$. (This means that R has greater resolution than Q and that Q has greater resolution than P). Last, the two high-resolution spectra Q and R vanish whenever U has components along eigenvectors corresponding to zero-valued eigenvalues of the crosspower spectrum matrix.

The relationship between the spectra P, Q, and R and the maximum entropy frequency-wavenumber spectrum is now being investigated. It has been determined that none of these spectra is a maximum entropy spectrum. Furthermore, the spectrum Q cannot be inverse transformed to yield the original crosspower spectrum matrix as can be the conventional spectrum P.

Currently, maximum entropy spectra for a symmetric planar array are being numerically inverse transformed yielding particular cross-

power spectral matrices for which the maximum entropy spectra are known. These efforts are directed toward discovering the function of the crosspower spectral matrix which provides the corresponding maximum entropy spectrum.

Plans for the fourth quarter are to determine which of the two high-resolution spectra, Q and R, is most nearly consistent with the original spectral matrix and to continue preliminary studies directed toward extending the K-line technique to multidimensional arrays of seismometers.

Task G - Study of Minimum Phase Equalization

Investigate the use of minimum-phase filters for intra-array equalization.

A survey of previous work on the Large Array Signal and Noise Analysis project has been completed, and plans are presently being drawn for continuing and completing that research during the fourth quarter.

Task H - Special Problems

The objective of this task is to develop and evaluate a procedure for theoretically estimating the SNR improvements which might be obtained by adding a small number of additional sensors to an existing array.

The first step in the process involves approximating the measured noise field at the existing array at each frequency by various combinations of directional and isotropic noise. After satisfactory noise models are obtained, locations of additional sensors are determined by positioning the new sensors so that the sum of the array straight sum responses to the noise models at selected frequencies is minimized.

Prior to the last quarter, a station where the noise field is relatively simple and time stationary was selected for evaluation of this process. The noise field at the array site was estimated and a theoretical

model of the noise at 1.5 Hz was formulated. This noise model was rather complex, consisting of 14 shifted disks each centered at one of the different reject areas observed in the measured-noise MCF response.

During the last quarter this noise model was rejected in favor of a much simpler one consisting of point sources and an annulus corresponding to the local surface-wave velocity. The new noise model provided a better estimate of the actual noise field at 1.5 Hz. Noise models were formulated for frequencies 0.5 and 1.0 Hz also. These models consist of both shifted disks and point sources.

To determine how well the theoretical noise models approximate the noise field at the array site, MCF's are designed from the theoretical noise cross-power matrices and their wavenumber responses computed. These wavenumber responses were compared with the wavenumber responses of the measured noise MCFs. The theoretical and measured noise MCF's were also cross-applied to the noise matrices.

In all cases the theoretical and measured noise MCF response compared favorably. The measured noise MCFs performed well when applied to the theoretical noise matrices, but the performance of the theoretical MCFs when applied to the measured noise matrices was not as good. Some thoughts concerning reasons for this are presented in the forthcoming special report.

The noise models were assumed to be good approximations of the measured noise and locations of additional sensors were determined. Two cases were investigated:

- Sets of 1, 2 and 3 sensors were added to the existing array with the restriction that the approximate overall dimension of the array be retained.

- The restriction was changed to allow new sensor locations anywhere out to 4 km from the center of the existing array.

In each case the additional sensor locations were restricted to points on a grid of approximately 0.5 km spacing. The straight sum response of the augumented array was computed at the points in frequency-wavenumber space corresponding to noise sources in the theoretical models, and sensor locations selected for which the straight sum response was a minimum.

Each of the six array modifications were evaluated by designing and MCF from the theoretical noise cross-power matrix at each frequency and applying the MCF and a straight summation process to the theoretical noise model to determine the SNR improvement.

The case in which the array dimensions were allowed to increase resulted in slightly larger improvements through straight-sum processing but the MCF improvements were about the same. The best overall improvement was obtained through MCF processing when 3 additional sensors were added to the existing array while retaining the present array dimension. In this case the SNR improvements were approximately 5 db at 0.5 Hz, 3.5 db at 1.0 Hz, and 1.0 db at 1.5 Hz.

This investigation has been completed, and a detailed presentation of the results in the form of a special report is now in preparation.

FINANCIAL STATUS

Financial status as of 31 October 1968 was reported on the Alternate Management Summary Report submitted 27 November 1968.

ACTION REQUIRED BY AFTAC

None

Yours very truly,

TEXAS INSTRUMENTS INCORPORATED

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GH:cjt

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Texas Instruments Incorporated Science Services Division P. O. Box 5621, Dallas, Texas 75222	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP
3. REPORT TITLE ADVANCED ARRAY RESEARCH, QUARTERLY REPORT NO. 3	
4. DESCRIPTIVE NOTES (Type of report and inclusive dates) Quarterly Report No. 3, 1 September 1968 through 30 November 1968	
5. AUTHOR(S) (First name, middle initial, last name) Hair, George D.	

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
5 December 1968	18	2

8a. CONTRACT OR GRANT NO. F33657-68-C-0867 b. PROJECT NO. VT/7701 c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

10. DISTRIBUTION STATEMENT

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11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
ARPA Order No. 624 ARPA Program Code No. 7F10	Advanced Research Projects Agency Department of Defense, The Pentagon Washington, D.C. 20301

13. ABSTRACT

Progress during the third quarter and plans for the fourth quarter are reported by task. Tasks reported are: Research on Adaptive Processing Techniques, Evaluation of the Expanded SP Array and the 7-element LP Array at TFO, Research on Array Processing Techniques for 3-component LP Arrays, NORSAR Signal and Noise Analysis, Analysis of Special WMO Noise Data, Research on High-Resolution Frequency-Wavenumber Spectral Estimation and Research on Methods for Predicting Improvement in Array Performance Achievable through Array Expansion. ( )

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Seismic Arrays						
Array Processing						
Adaptive Processing						
Expanded TFO Short-Period Array						
Long-Period Array Processing						
NORSAR						
Wavenumber Spectra						